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Slotted High-Harmonic Peniotron Oscillator

Final Progress Report

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Slotted High-Harmonic Peniotron Oscillator

1.0 Publications and Conference Proceedings during Period 6/30/94 - 6/29/97

"Slotted Third-Harmonic Peniotron Forward-Wave Oscillator," A.T. Lin, C.K. Chong, D.B. McDermott, A.J. Balkcum, F.V. Hartemann, and N.C. Luhmann, Jr., Proc. of *SPIE Conf. on High Power Microwaves*, Los Angeles, CA, 1994.

"Third-Harmonic Slotted Forward-Wave Peniotron," A.T. Lin, C.K. Chong, D.B. McDermott, A.J. Balkcum, F.V. Hartemann, and N.C. Luhmann, Jr., *Digest of 19th Int. Conf. on Infrared and Milimeter Waves*, Sendai, Japan, 1994.

2.0 Overview

This work has been concerned with RF generation utilizing vacuum electronics. The novel, highly efficient peniotron interaction has been studied experimentally and theoretically. The peniotron developments borrow from the P.I.'s recent successes in the field of high power gyro-TWT amplifiers [1]. The concept that mode selective circuits can be used to realize high power harmonic gyro-TWT amplifiers, which has been verified by the PI's experimental group, has been extended to peniotrons for the design of an efficient high power peniotron oscillator. The peniotron is predicted to generate 120 kW with an unprecedented conversion efficiency of 63%. A mode selective circuit is employed to suppress competing modes without the desired azimuthal symmetry by interrupting their wall currents [2]. This removes the obstacle blocking the development of peniotrons. Although the peniotron interaction is more efficient, the gyrotron interaction is significantly stronger. The peniotron will thereby ordinarily be suppressed before it has a chance to grow.

Peniotrons [3-5] are an extremely promising, efficient source of high power, millimeter-wave radiation because they can yield extremely high efficiency (50-75%). Harmonic peniotrons offer the additional feature of reducing the required magnetic fields. Furthermore, slotted circuits can be used to increase the interaction strength for low voltage electron beams.

The asynchronous resonance condition for an $(m-1)^{th}$-harmonic TE_{m1} peniotron with an axis-encircling electron beam is $\omega = (m-1)\Omega_c$. As shown in Fig. 1, the electrons advance by one cycle in the wave as they complete one gyro-orbit. The electrons effectively experience the TE_{m1} wave as a plane wave, resulting in an $\underline{E}\times\underline{B}$ drift of the guiding centers toward the azimuth where they are phased to lose energy. Due to the rf field's radial gradient, each electron will lose more energy than it gains. The reason for the device's extremely high overall efficiency is that all electrons follow the same trajectory, and lose energy to the wave. Phase trapping does not occur.

In addition to the theoretical work, experimental research has also been performed. A promising third-harmonic peniotron in slotted waveguide that was proposed by Dr. Lin was built and tested. Unfortunately, the preliminary experiments were unsuccessful.

3.0 Progress

The research on peniotrons took two paths. An experiment was built and tested. Also, the design of a high efficiency peniotron in a mode selective circuit was developed.

3.1 Experimental Progress

A preliminary experiment has been conducted to test a novel, efficient, slotted third-harmonic peniotron interaction, which is predicted [6] by a nonlinear, multi-mode PIC simulation code to yield 110 kW with 45% efficiency. The asynchronous cyclotron-resonance peniotron interaction has been found in simulation to be much more efficient than the synchronous gyrotron cyclotron-resonance interaction, but is easily dominated by the stronger gyrotron interaction. Operation at the s^{th} harmonic allows the magnetic field to be reduced by a factor of s, but requires a high voltage electron beam for strong interaction in a conventional smooth-bore cylindrical circuit. However, a slotted interaction waveguide significantly increases the strength of high harmonic interactions for low voltage electron beams. The simulation found that by configuring the oscillator so that the peniotron is excited as a forward wave at the cutoff frequency of a travelling-wave circuit, the peniotron will dominate the usually stronger gyrotron interaction due to the

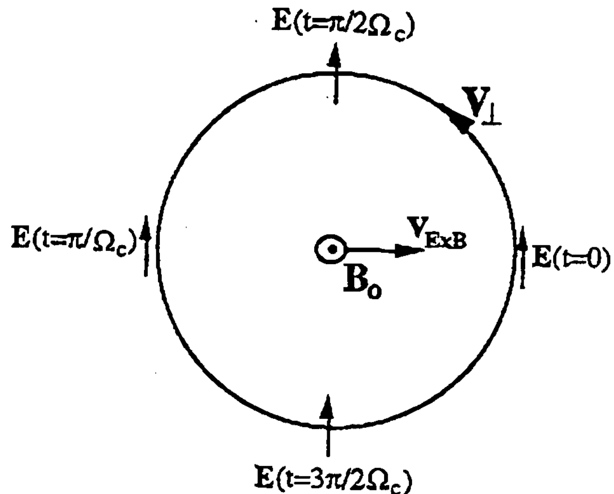

Fig. 1. Schematic of high-harmonic TE_{m1} peniotron interacton with an axis-encircling electron beam showing the rf field at four times during a gyro-orbit and the resulting ExB drift..

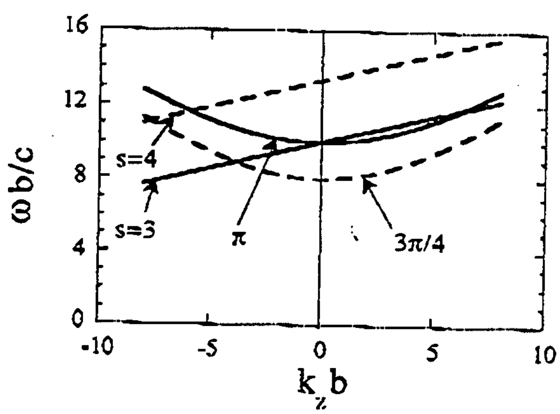

Fig. 2. Dispersion diagram of the third-harmonic slotted peniotron forward-wave oscillator showing the third and fourth harmonic cyclotron resonance lines and the π and 3π/4 modes.

stronger interaction impedance that exists near cutoff. The dispersion diagram for the slotted third-harmonic peniotron oscillator is shown in Fig. 2. The third-harmonic cyclotron resonance line intersects the π mode of a terminated, nonresonant, slotted eight-vane waveguide at its cutoff frequency. Although many potential harmonic gyrotron

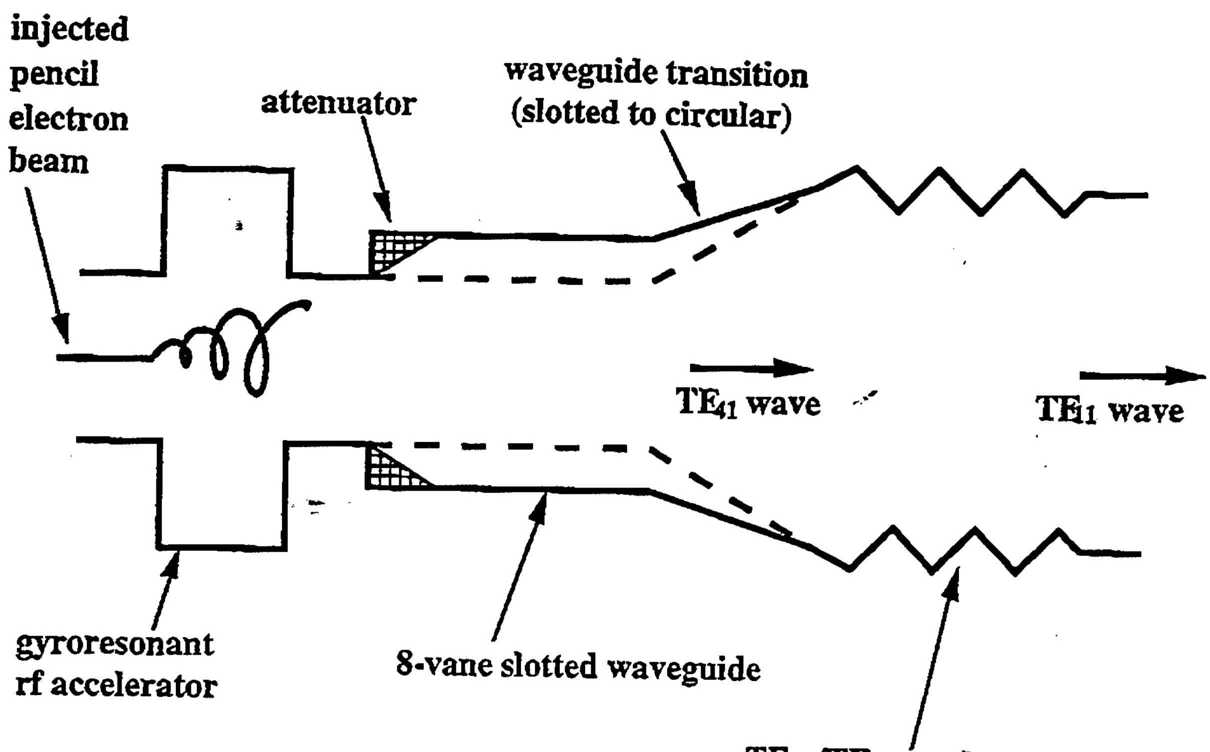

Fig. 3. Schematic of the slotted third-harmonic peniotron traveling-forward-wave oscillator proof-of-principle experiment.

intersections are evident, the third-harmonic peniotron is predicted to dominate.

In order to test this novel, efficient oscillator, the experiment shown in Fig. 3 was built for operation at 10 GHz. The parameters are the same as in the PIC simulation (Table I). It is crucial that the interaction circuit be terminated on both ends so that it is nonresonant. In this way, interactions at the cutoff frequencies are emphasized. The traveling-wave circuit is terminated on the electron-source end by a load consisting of tapered wedges of absorbing dielectric in each of the eight slots. The interaction region ends with a transition from the slotted structure to circular waveguide to convert the π mode into the TE_{41} mode, which is then transformed into the TE_{11} mode in a four-period corrugated

Table I. Design Parameters of the 10 GHz Third-Harmonic Slotted Peniotron Forward-Wave Oscillator.

Beam Voltage	70 kV
Beam Current	3.5A
$v_\perp/v_z$	1.3
Magnetic Field	1.3 kG
Cutoff Frequency	9.94 GHz
Mode	π mode
# Vanes	8
Inner Circuit Radius, a	0.80 cm
Outer Circuit Radius, b	1.30 cm
r_c/a	0.0
r_L/a	0.7
$\Delta v_z/v_z$	5 %
$\Delta r_c/a$	10 %
Interaction Length	20.3 cm

beat-wave mode converter [7], whose conversion efficiency was measured to be 98% at its center frequency as shown in Fig. 4. Finally, a circular to rectangular waveguide transition after the circular vacuum window allows the output to be measured with standard waveguide components. The slotted X-band circuit was fabricated by electric discharge wire machining. The individual circuit elements are bolted together into a vacuum chamber within the bore of a solenoid magnet. Although we are currently in the process of acquiring a Cusp electron gun from Northrop-Grumman [9] that will produce axis-encircling electron beams and would be appropriate for microwave generation at 35 GHz, our gyroresonant rf accelerator [8] was employed for producing the axis-encircling electron beams to test this novel peniotron oscillator.

The preliminary experiment was unsuccessful. Forward-wave oscillation was not achieved in the terminated travelling-wave circuit. Unfortunately, the circuit had not been configured so that the excitation of the more conventional backward-waves could be measured.

3.2 Theory

The objective of the theoretical work was to develop the design for a peniotron oscillator that is as free of risks as possible in order to realize the high efficiency predicted for the peniotron. The approach is to operate a peniotron at the first harmonic in the TE_{21} mode, which is the most basic peniotron interaction. For the excitation of a TE_{mn} mode, axis-encircling electrons can only be gyro-resonant at the m^{th}-harmonic and penio-resonant at the $(m-1)^{st}$-harmonic, which alleviates mode competition considerably. The peniotron was designed for the 70 kV, 3 A axis-encircling electron beam produced by

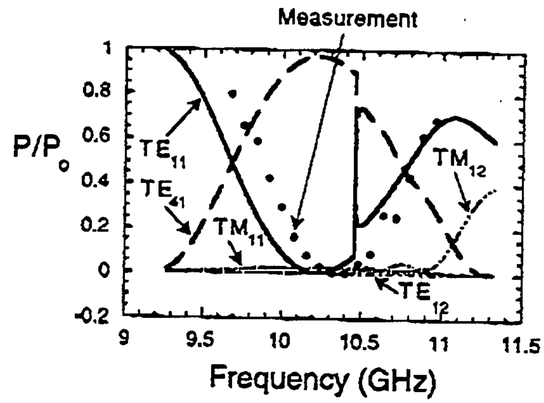

Fig. 4. Bandwidth of the four-period beat-wave TE_{41}/TE_{11} mode converter showing the predicted power distribution in the various modes for a TE_{11} input wave and the TE_{11} power remaining from measurement (solid circles).

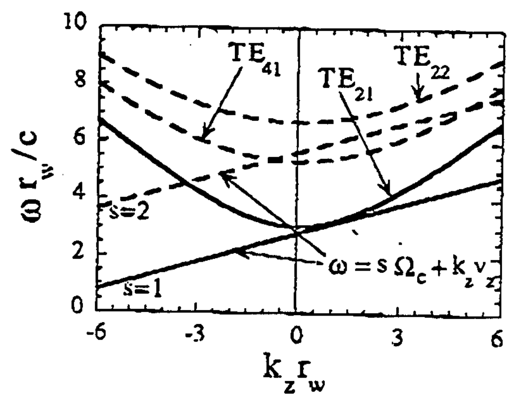

Fig. 5. Dispersion diagram of the first-harmonic TE_{21} peniotron oscillator showing the first and second harmonic cyclotron resonance lines.

Northrop Grumman's Cusp Gun [9]. The dispersion diagram for the proposed TE_{21} peniotron with a mode-selective cavity is shown in Fig. 5. The cavity has been sliced axially with four cuts separated in azimuth by 90° to suppress the odd-order azimuthal modes by interrupting their wall currents [2]. Such a circuit was employed by the P.I. in a recent successful second-harmonic TE_{21} gyro-TWT amplifier experiment [1]. The sliced circuit resulted in a loss of ~1 dB/wavelength for the odd-order modes, while the even-order modes

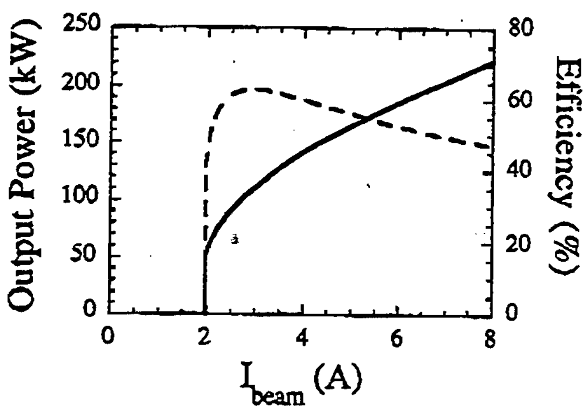

Fig. 6. Predicted output power and conversion efficiency for sliced TE_{21} peniotron (Table II).

Table II. Design Parameters of the 16 GHz Sliced TE_{21} Peniotron.

Beam Voltage	70 kV
Beam Current	3A
$v_\perp/v_z$	2.0
r_c/a	0.0
Magnetic Field	6.5 kG
Frequency	16.0 GHz
Mode	TE_{21}
Cavity Radius	0.92 cm
Cavity Length	9.2 cm

were negligibly affected. The tremendous advantage of this configuration for the peniotron is that there is no first-harmonic gyrotron interaction to compete with. The stongest competing interaction is at the second harmonic in operating TE_{21} mode, but the intersection occurs for such a high-order axial mode that the low diffraction-coupled Q will quench the oscillation.

The large-signal characteristics of the slced TE_{21} peniotron described in Table II were evaluated with a gyrotron/peniotron particle-tracing simulation code. The oscillator is predicted to generate an output power of 120 kW with an unprecedented conversion efficiency of 63%, as shown in Fig. 6. This efficiency is state-of-the-art and higher than any values reported for laboratory or commercial gyrotrons. We intend to test this device with the Cusp electron gun currently being acquired from Northrop-Grumman.

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